

# Other Beyond Standard Model Searches at the Tevatron

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We present the results of searches for non-standard model phenomena, with focus on signature-based searches and searches driven by non-supersymmetry (non-SUSY) models. The analyses use 1.0–2.5 fb<sup>-1</sup> of data from  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV collected with the CDF and D0 detectors at the Fermilab Tevatron. No significant excess in data has been observed. We report on the event counts, kinematic distributions, and limits on selected model parameters.

## 1. INTRODUCTION

The standard model (SM) of elementary particle physics describes the structure of fundamental particles and how they interact via gauge bosons. To date, almost all experimental results have agreed with the prediction by the standard model. However, many questions can be raised, which indicate that the standard model is not complete. For example, “Why is there a hierarchy between the electroweak scale (1 TeV) and the gravitational scale (10<sup>16</sup> TeV)?”, “What are the origins of mass?”, “Why is there a spectrum of fermion masses? Are there only three generations?”, *etc.* Although the most popular extension of the standard model is supersymmetry (SUSY), there are other equally well-motivated models, such as extra dimension, compositeness, 4<sup>th</sup> generation, technicolor, *etc.* In this document, we present results of signature-based searches and searches inspired by non-SUSY models, using 1.0–2.5 fb<sup>-1</sup> of data collected with the CDF and D0 detectors. In signature-based searches, we apply generic selection criteria in order to be sensitive to a wide range of new physics. We report on the event counts and various kinematic distributions of data and predicted backgrounds. In model-inspired searches, we optimize selection criteria to obtain the best sensitivity for selected models. If no significant excess is found, we report limits on model parameters.

## 2. RESULTS OF BEYOND STANDARD MODEL SEARCHES AT THE TEVATRON

### 2.1. Search for Anomalous Production of $\gamma bj\cancel{E}_T$

The CDF collaboration has performed a signature-based search in the inclusive  $\gamma bj\cancel{E}_T$  final state using 2.0 fb<sup>-1</sup> of data. The  $\gamma bj\cancel{E}_T$  signature raised great interest for two main reasons. First, this final state has been predicted by several SUSY models<sup>1</sup>[2, 3], *e.g.*, the production of a chargino and a neutralino, when  $\tilde{\chi}_2^0$  is photino-like and the LSP  $\tilde{\chi}_1^0$  is Higgsino-like, via the decay chain:  $\tilde{\chi}_1^+ \tilde{\chi}_2^0 \rightarrow (\bar{b}\tilde{t})(\gamma\tilde{\chi}_1^0) \rightarrow (\bar{b}c\tilde{\chi}_1^0)(\gamma\tilde{\chi}_1^0) \rightarrow (\gamma\bar{b}c\cancel{E}_T)$ . Second, the dominant backgrounds are mis-identifications of either the photon or the  $b$ -quark candidates and mismeasurements of the jet energy which induce  $\cancel{E}_T$  not associated with unobserved neutral particles (fake  $\cancel{E}_T$ ). The SM processes which produce real  $\gamma bj\cancel{E}_T$  are expected to contribute at most 2%. Therefore, a significant excess in data will be an indication of new physics. Events are required to have a central<sup>2</sup> photon with transverse energy  $E_T > 25$  GeV, at least two jets with  $E_T > 15$  GeV and  $|\eta^{\text{det}}| < 2.0$ , at least one of the jets must be identified as originating from a  $b$  quark (“ $b$ -tagged”) using the tight SECVTX algorithm [4], and missing transverse energy  $\cancel{E}_T > 25$  GeV. Figure 1 shows the  $\cancel{E}_T$  and dijet mass  $M_{ij}$  distributions from data and predicted background. Other kinematic distributions, such as

<sup>1</sup>These models had been proposed to explain the CDF  $ee\gamma\gamma\cancel{E}_T$  event observed in Run I [1].

<sup>2</sup>Throughout this document, all central objects have detector pseudo-rapidity  $|\eta^{\text{det}}| < 1.1$ .

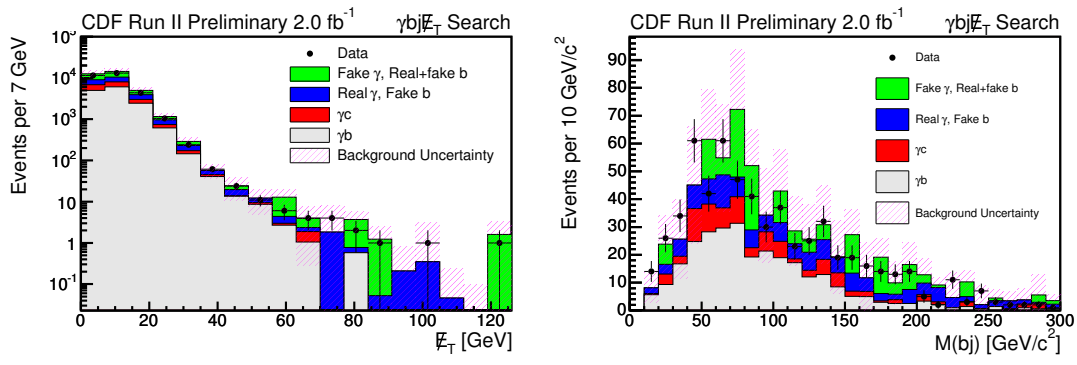


Figure 1: CDF search for anomalous production of  $\gamma b j E_T$ : the  $E_T$  (left) and  $M_{bj}$  (right) distributions observed (markers) and background prediction (filled histograms). The hatched-region indicates the total uncertainty on the predicted background in each bin.

jet multiplicity,  $E_T$  of photon,  $E_T$  of  $b$ -tagged jet, *etc.*, have also been examined and no significant excess has been found. The observed number of events in data is 617, which is consistent with the expected number of background events,  $637 \pm 139$ .

## 2.2. Search for Anomalous Production of $\ell \gamma b E_T$ and Measurement of SM $t\bar{t}\gamma$ Production Cross-section

Ref. [2] predicts in the Minimal Supersymmetric Standard Model (MSSM) an exotic decay channel of the top quark, which may compete with  $t \rightarrow Wb$ , into a light stop and a light Higgsino-like neutralino. A  $t\bar{t}$  pair may then decay via  $t\bar{t} \rightarrow Wb\tilde{\chi}_i^0 \rightarrow \ell\bar{\nu}_\ell b c \tilde{\chi}_1^0 \tilde{\chi}_1^0 \gamma + X$ . Instead of searching for this MSSM model only, the CDF collaboration has performed a model-independent search in the inclusive  $\ell \gamma b E_T$  final state using  $1.9 \text{ fb}^{-1}$  of data, where  $\ell$  is an electron or a muon. Since this signature is rare, the  $E_T$  and  $b$ -tagging requirements are looser than those in Section 2.1: a central electron or muon with  $p_T > 20 \text{ GeV}$ , a central photon with  $E_T > 10 \text{ GeV}$ , at least one jet which is  $b$ -tagged by the loose SECVTX algorithm [4], and  $E_T > 20 \text{ GeV}$ . Figure 2 shows the jet multiplicity and  $H_T^3$  distributions from the inclusive  $\ell \gamma b E_T$  final state. No significant excess in data is found: 28 observed and  $27.9^{+3.6}_{-3.5}$  expected. The background has a significant contribution from the SM  $t\bar{t}\gamma$  production, especially in the lepton + jets channel. After requiring  $H_T > 200 \text{ GeV}$  and two additional jets ( $\geq 3$  jets with  $\geq 1$   $b$ -tag in total), the  $t\bar{t}\gamma$  cross-section has been measured to be  $0.15 \pm 0.08 \text{ pb}$ , which is consistent with the next-to-leading-order (NLO) prediction,  $0.080 \pm 0.012 \text{ pb}$  [5].

## 2.3. Search for Anomalous Production of $\gamma\gamma E_T$

Anomalous production of inclusive  $\gamma\gamma E_T$  events has been predicted by many models, such as gauge-mediated SUSY breaking [6], fermiophobic Higgs [7], 4<sup>th</sup> generation [8], and the  $E_6$  model [9]. The CDF collaboration has carried out a signature-based search using  $2.0 \text{ fb}^{-1}$  of data. Two central photons with  $E_T > 13 \text{ GeV}$  are required. The non-collision backgrounds from beam halos and cosmic rays are suppressed by requiring photons to be in time with a  $p\bar{p}$  collision, where the photon time is measured with a novel timing system (EM Timing) [10]. Instead of making a tight requirement on  $E_T$ , this analysis selects events with large “ $E_T$  significance”. A data-based model predicts the

<sup>3</sup>The  $H_T$  is defined as the scalar sum  $p_T$  of all identified objects in an event.

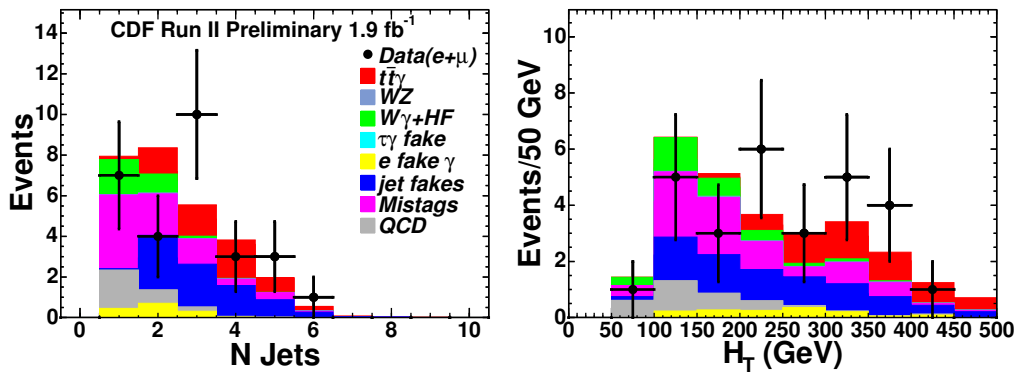


Figure 2: CDF search for anomalous production of  $l\gamma bE_T$ : the jet multiplicity (left) and  $H_T$  (right) distributions observed (markers) and background prediction (filled histograms). The contribution of SM  $t\bar{t}\gamma$  increases as the jet multiplicity and  $H_T$  increase.

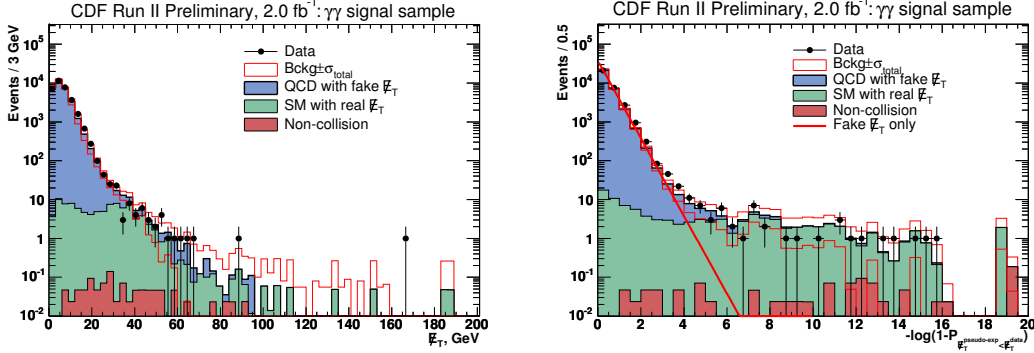


Figure 3: CDF search for anomalous production of  $\gamma\gamma E_T$ : the  $E_T$  (left) and  $E_T$  significance (right) distributions observed (markers) and background prediction (filled histograms). The  $E_T$  significance is defined as  $-\log(1 - \mathcal{P}_{E_T^{\text{pseudo-exp}} < E_T^{\text{data}}})$ , namely how often the observed  $E_T$  is larger than a  $E_T$  value which is randomly picked from the predicted fake  $E_T$  distribution.

fake  $E_T$  distribution induced by mis-measurement of jet energies and soft unclustered energies<sup>4</sup> and calculates the  $E_T$  significance event by event. Figure 3 shows the distributions of  $E_T$  and  $E_T$  significance in the diphoton sample. A minimum requirement on the  $E_T$  significance removes events with large, fake  $E_T$  and keeps a good acceptance for events with small, real  $E_T$  which would have been rejected by a straight  $E_T$  cut. For  $E_T$  significance greater than 5, 34 events are observed in data, which is consistent with the background expectation,  $48.6 \pm 7.5$ . Note that the QCD multi-jet or diphoton+jet events are largely removed and the events selected are mostly SM  $W\gamma$  events with real  $E_T$ <sup>5</sup>.

## 2.4. Model-independent Global Search for New Physics

The CDF collaboration has performed a model-independent global search in  $2.0 \text{ fb}^{-1}$  of data which contain over four million high- $p_T$  events [11, 12]. This global search has three algorithms: VISTA, BUMP HUNTER, and SLEUTH, and aims to look for new physics in every possible final state without bias toward any new physics model. The first algorithm, VISTA, searches for discrepancies in the total event counts and shapes of kinematic distributions. Data

<sup>4</sup>The soft unclustered energies refer to energies not included by jet reconstruction algorithms and are from underlying events or multiple interactions.

<sup>5</sup>Here, the lepton from  $W$  is misidentified as one of the photons.

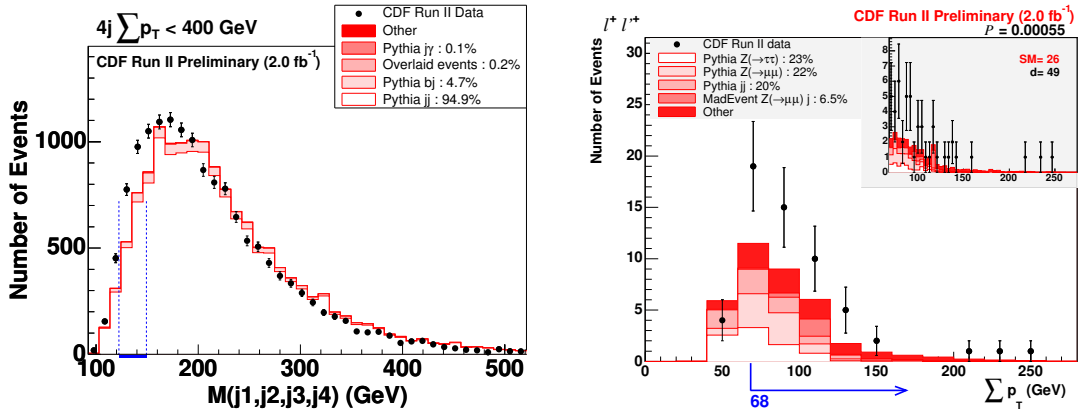


Figure 4: CDF model-independent global search. The left figure shows the only significant bump found by BUMP HUNTER, the invariant mass of all four jets in the 4-jet final state, as indicated by the blue dashed lines. The right figure shows the final state with the most significant excess in the  $\Sigma p_T$  distribution found by SLEUTH, same-sign dilepton with different flavors and  $\Sigma p_T > 68$  GeV/c.

are partitioned into 399 exclusive final states according to combinations of detectable objects:  $\gamma$ ,  $e$ ,  $\mu$ ,  $\tau$ ,  $b$ -jet, jet, and  $\cancel{E}_T$ . All objects are required to have  $p_T \geq 17$  GeV/c. The background prediction is estimated with Monte Carlo (MC) using standard HEP event generators and CDF detector simulation. The  $k$ -factors for the SM cross-sections and the data to MC scale factors for the object efficiencies and mis-identification probabilities are determined from data by a global fit to all final states. After accounting for the trials factor associated with looking at so many final states, no significant discrepancy is found in the event counts, but 555 out of 19,650 kinematic distributions have significant different shapes between data and background prediction. Careful investigations show that these discrepancies are attributed to the difficulty in modeling soft QCD jet radiation in the simulation. The second algorithm, BUMP HUNTER, searches for narrow resonances in invariant mass distributions. The search window is defined based on the expected detector resolution. Out of 5036 invariant mass distributions, the only significant bump found is the invariant mass of all four jets in the 4-jet final state (see Figure 4). However, this bump arises from the same, imperfect modeling of soft QCD jets seen in VISTA. The third algorithm, SLEUTH, assumes new physics appears as excess in the tail of scalar sum  $p_T$  ( $\Sigma p_T$ ) distributions. For each final state, SLEUTH determines the semi-infinite region of  $\Sigma p_T$  which has the most significant excess in data. Figure 4 shows the final state with the most significant region. After taking into account the trials factor,  $\sim 8\%$  of hypothetical similar CDF experiments would have produced a more significant region purely by fluctuations of the SM background. The results of all three global-search algorithms have not yet shown evidence of new physics.

## 2.5. Search for Large Extra Dimensions in $\gamma \cancel{E}_T$

The CDF and D0 collaborations have looked for indications of large extra dimensions (LED) [13] in 2.0 fb<sup>-1</sup> and 1.1 fb<sup>-1</sup> of data, respectively [14, 15]. In the LED model, the production  $q\bar{q} \rightarrow \gamma G$  gives an exclusive  $\gamma \cancel{E}_T$  final state where the  $\cancel{E}_T$  arises from the massive and non-interacting graviton. The analyses require one central photon with  $E_T > 90$  GeV and  $\cancel{E}_T > 50/70$  GeV for CDF/D0. Events with extra high  $p_T$  tracks or jets are removed. The exclusive  $\gamma \cancel{E}_T$  final state suffers from large amount of cosmic rays and beam halos and the analysis would have been impossible if an effective rejection was not applied. The CDF analysis requires the photon to be in time with a  $p\bar{p}$  collision and uses topological variables to separate signal from non-collision background, such as track multiplicity, angular separation between the photon and the closest hit in the muon chamber, and energy deposited in the calorimeters. The D0 analysis utilizes the transverse and the unique longitudinal segmentation of the electromagnetic (EM) calorimeter. The photon trajectory is reconstructed by fitting one measurement in the preshower detector and four in the EM calorimeter to a straight line (EM pointing algorithm). The  $z$  position and the transverse impact parameter of the

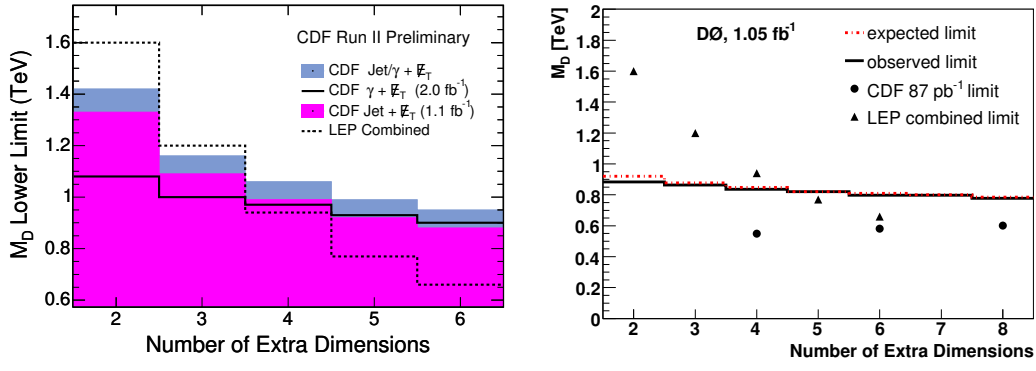


Figure 5: Search for large extra dimensions in  $\gamma E_T$  the 95% CL lower limits on the fundamental Planck mass  $M_D$  vs. number of extra dimensions from CDF (left) and D0 (right), compared with the limits set by the LEP experiments. A combined limit from the two LED searches at CDF, using  $\gamma E_T$  and monojet+ $E_T$  final states, is also shown.

Table I: Expected and observed lower mass limits for  $Z'$  boson with SM coupling and those predicted by the  $E_6$  model. These limits have been set by CDF using the results of search for high-mass  $ee$  resonances.

	$Z'_{SM}$	$Z'_{\psi}$	$Z'_{\chi}$	$Z'_{\eta}$	$Z'_I$	$Z'_{sq}$	$Z'_N$
Exp. Limit ( $\text{GeV}/c^2$ )	965	849	860	932	757	791	834
Obs. Limit ( $\text{GeV}/c^2$ )	966	853	864	933	737	800	840

photon, at the point of closest approach with respect to the beam line, are required to be within 10 cm and 4 cm of a  $p\bar{p}$  interaction vertex, respectively<sup>6</sup>. The distribution of the transverse impact parameter is further used to estimate the amount of remaining non-collision background. After all selections, the dominant background in both analyses is SM  $Z\gamma \rightarrow \nu\nu\gamma$  production. Both analyses have not found significant excess in data: 40 observed vs.  $46.3 \pm 3.0$  expected (CDF) and 29 observed vs.  $22.4 \pm 2.5$  expected (D0). Lower limits on the fundamental Planck scale,  $M_D$ , are set at 95% confidence level (CL) as a function of the number of extra dimensions,  $n$  (see Figure 5). For  $n = 4$ , the lower limit on  $M_D$  is 970 GeV for CDF and 836 GeV for D0. The Tevatron results supersedes the LEP limits [16] when  $n > 3$  for CDF and when  $n > 4$  for D0.

## 2.6. Search for High-mass $ee$ and $\gamma\gamma$ Resonances

Many extensions of the standard model have predicted new particles which decay to a lepton-lepton or photon-photon pair, such as Randall-Sundrum (RS) graviton [17] and  $Z'$  from the  $E_6$  model [18]. The CDF and the D0 collaborations have searched for high-mass resonances in the  $ee$  and  $ee/\gamma\gamma$  final states, using 2.5 and 1.0  $\text{fb}^{-1}$  of data, respectively [19]. The CDF analysis requires two electrons in the central-central or central-forward<sup>7</sup> region while the D0 analysis requires two electromagnetic (EM) objects<sup>8</sup> in the central-central region; the CDF electrons and the D0 EM objects must have  $E_T > 25$  GeV each. Figure 6 shows the  $M_{ee}$  and  $M_{ee/\gamma\gamma}$  spectra from CDF and D0, individually. The dominant background is SM Drell-Yan production (and also diphoton production for D0). The D0 data are consistent with the background prediction while the CDF data have a  $3.8\sigma$  excess for the mass window  $228 < M_{ee} < 250 \text{ GeV}/c^2$ . The probability (or the  $p$ -value) to observe such an excess anywhere in the search window

<sup>6</sup>The resolution of both the  $z$  position and the transverse impact parameter is about 2 cm.

<sup>7</sup>The forward electrons have detector pseudo-rapidity  $1.2 < |\eta^{\text{det}}| < 2.0$ .

<sup>8</sup>The EM objects have no requirements on tracks and include both electrons and photons.

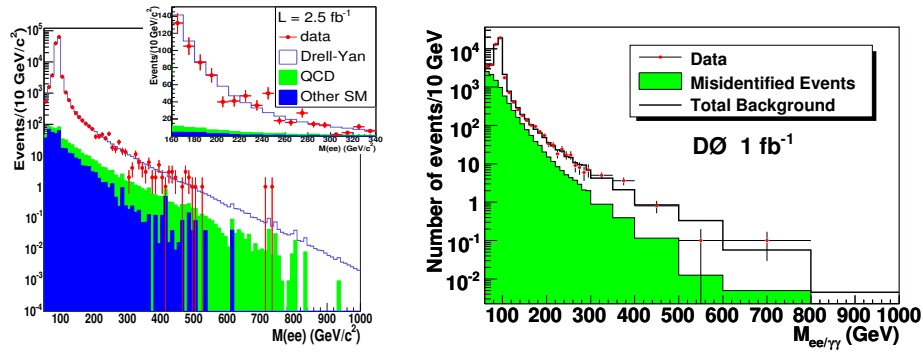


Figure 6: Search for high-mass  $ee, \gamma\gamma$  resonances: the  $M_{ee}$  spectrum from CDF (left) and  $M_{ee,\gamma\gamma}$  spectrum from D0 (right), observed (markers) and background prediction (filled histograms). The CDF data have a  $3.8 \sigma$  excess for the mass window  $228 < M_{ee} < 250$  GeV/c<sup>2</sup>.

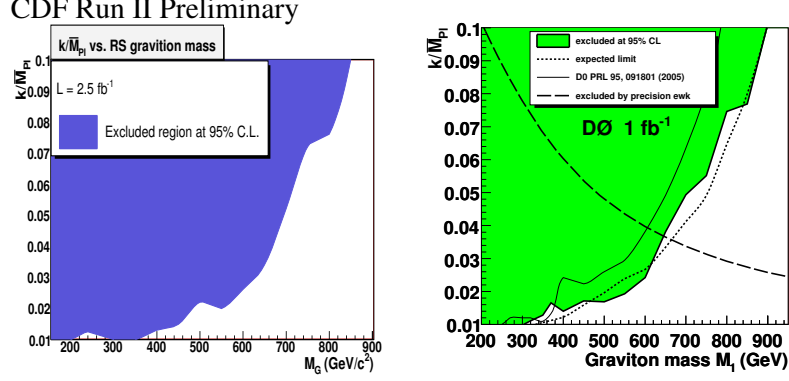


Figure 7: The excluded regions of RS graviton mass with respect to  $k/\bar{M}_{Pl}$  from CDF (left) and D0 (right).

$150 < M_{ee} < 1000$  GeV/c<sup>2</sup> is 0.6%. Without significant excess in both analyses, CDF and D0 set limits on the mass of RS graviton with respect to the coupling between the RS graviton and the SM particles,  $k/\bar{M}_{Pl}$ <sup>9</sup> (see Figure 7). For  $k/\bar{M}_{Pl} = 0.1$ , masses below 850 (CDF) and 900 (D0) GeV/c<sup>2</sup> are excluded at 95% CL. CDF also sets the world's best lower mass limits for  $Z'$  boson with SM coupling and those predicted by the  $E_6$  model (see Table I).

## 2.7. Search for $W' \rightarrow e\bar{\nu}_e$

Additional charged gauge boson,  $W'$ , has been introduced by several new physics models, such as left-right symmetric model [20] and the  $E_6$  model [21]. The D0 collaboration has searched for a  $W'$  decaying to an electron and a neutrino using 1 fb<sup>-1</sup> of data [22]. Events are required to have a central electron with  $E_T > 30$  GeV and  $\cancel{E}_T > 30$  GeV. Clean-up cuts are applied to reduce mis-measured  $\cancel{E}_T$ . Data with transverse mass<sup>10</sup>  $m_T < 30$  GeV/c<sup>2</sup> and  $60 < m_T < 140$  GeV/c<sup>2</sup> are used to obtain the normalizations of QCD multi-jet and SM  $W \rightarrow e\bar{\nu}_e$  backgrounds, separately. There is no excess in the search window  $140 < m_T < 1000$  GeV/c<sup>2</sup> (see Figure 8). The shape of  $m_T$  distribution serves as a discriminant to separate the exotic signal from the SM background when setting the lower mass limit on  $W'$ . Using the Altarelli reference model [23] where SM couplings are assumed,  $W'$  with mass below

<sup>9</sup>Here,  $k$  is the warp factor which gives the curvature of extra dimension in the RS model and  $\bar{M}_{Pl}$  is the reduced Plank scale.

<sup>10</sup>The transverse mass is defined as  $m_T = \sqrt{2E_T^{e\ell}\cancel{E}_T(1 - \cos\Delta\phi)}$ , where  $E_T^{e\ell}$  is the transverse energy of electron and  $\Delta\phi$  is the azimuthal angle between the electron and missing energy.

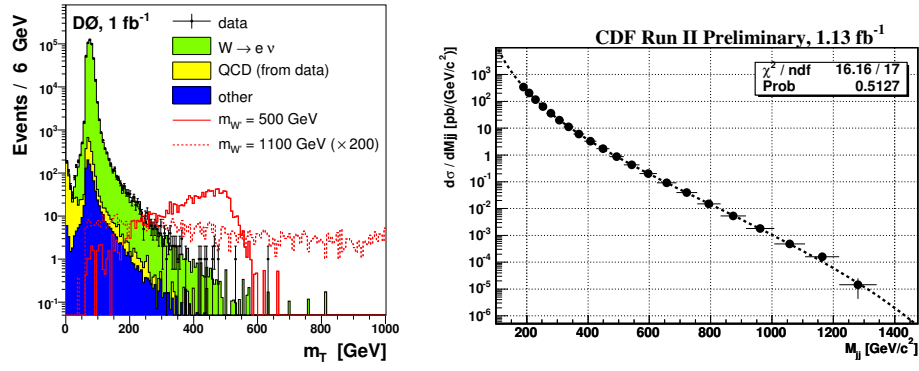


Figure 8: The left figure shows the distribution of transverse mass,  $m_T$ , observed (markers) and background prediction (filled histograms) from the D0 search for  $W' \rightarrow e\bar{\nu}_e$ . The expected  $m_T$  distributions for  $W'$  with masses at 500 GeV/ $c^2$  and 1100 GeV/ $c^2$  are also shown. The right figure shows the  $M_{jj}$  spectrum observed in the CDF data. The fit function,  $\frac{d\sigma}{dm} = p_0(1-x)^{p_1} / x^{p_2+p_3 \log x}$ , where  $x = m/\sqrt{s}$ , describes the data well.

1 TeV/ $c^2$  is excluded at 95% CL. This limit is currently the world's best limit.

## 2.8. Search for High-mass Dijet Resonances

New particles which decay into two energetic partons (quarks and gluons) are expected to produce a resonant structure in the dijet mass spectrum. Such new particles include excited quarks ( $q^* \rightarrow q\bar{q}$ ) [24], axigluons ( $A \rightarrow q\bar{q}$ ) [25], color octet techni- $\rho$  ( $\rho_T \rightarrow q\bar{q}, g\bar{g}$ ) [26],  $W'$  ( $W' \rightarrow q\bar{q}'$ ),  $Z'$  ( $Z' \rightarrow q\bar{q}$ ), diquarks in the string-inspired  $E_6$  model [ $D(D^c) \rightarrow (q\bar{q})\bar{q}\bar{q}$ ] [18], and Randall-Sundrum graviton ( $G \rightarrow q\bar{q}, g\bar{g}$ ) [17, 27]. The CDF collaboration has performed a search for high-mass dijet resonances in 1.1 fb $^{-1}$  of data. Events are required to have two central jets with invariant mass  $M_{jj} > 180$  GeV/ $c^2$  where the jet energy is corrected to the hadron level, and events must not have significant  $\cancel{E}_T$ . The background is completely dominated by the QCD dijet production. The measured  $M_{jj}$  spectrum is fit to a smooth function motivated by predictions of PYTHIA and HERWIG MC and calculations by the NLOJET++ program (see Figure 8). No excess of data above the fit is observed. This analysis has set the world's best limits on excited quarks, axigluon and coloron, color octet techni- $\rho$ , and  $E_6$  diquarks, and excluded the mass regions  $260 < M(q^*) < 870$  GeV/ $c^2$ ,  $260 < M_A < 1250$  GeV/ $c^2$ ,  $260 < M(\rho_T) < 1100$  GeV/ $c^2$ , and  $260 < M(D, D^c) < 630$  GeV/ $c^2$ , at 95% CL, respectively.

## 2.9. Search for New Physics in Exclusive $jj\cancel{E}_T$ and the Leptoquark Interpretation

The signature with exclusive dijet and large  $\cancel{E}_T$  has been predicted by leptoquarks [28], SUSY [29], Universal Extra Dimensions with conservation of the momentum in the volume of the extra dimensions [30], and Little Higgs with T-parity conservation [31]. The CDF collaboration has extended its previous monojet +  $\cancel{E}_T$  search to the  $jj\cancel{E}_T$  channel using 2.0 fb $^{-1}$  of data. Events are required to have exactly two jets with  $E_T > 30$  GeV and  $|\eta_{\text{det}}| < 2.4$ , no extra jets with  $E_T > 15$  GeV. Events containing EM objects and isolated tracks are removed. In order to be sensitive to different scenarios of new physics, two kinematic regions are defined. The “low kinematic region” must have  $\cancel{E}_T > 80$  GeV and scalar sum  $E_T$  of two jets  $E_T^{j1} + E_T^{j2} > 125$  GeV, while the “high kinematic region” must have  $\cancel{E}_T > 100$  GeV and  $E_T^{j1} + E_T^{j2} > 225$  GeV. The dominant backgrounds are SM productions of  $W + \text{jets} \rightarrow \ell\nu + \text{jets}$  with a missing lepton and  $Z + \text{jets} \rightarrow \nu\nu + \text{jets}$ . Data agree well with the background prediction: 2506 observed vs.  $2312 \pm 140$  expected (low kinematic) and 186 observed vs.  $196 \pm 29$  expected (high kinematic). The results are turned to limits on the masses of the first ( $LQ_1$ ) and the second generation scalar leptoquarks ( $LQ_2$ ). The leptoquarks are pair produced and both charge 1/3 and charge 2/3 leptoquarks are included. The  $LQ_1$  and  $LQ_2$  are assumed to

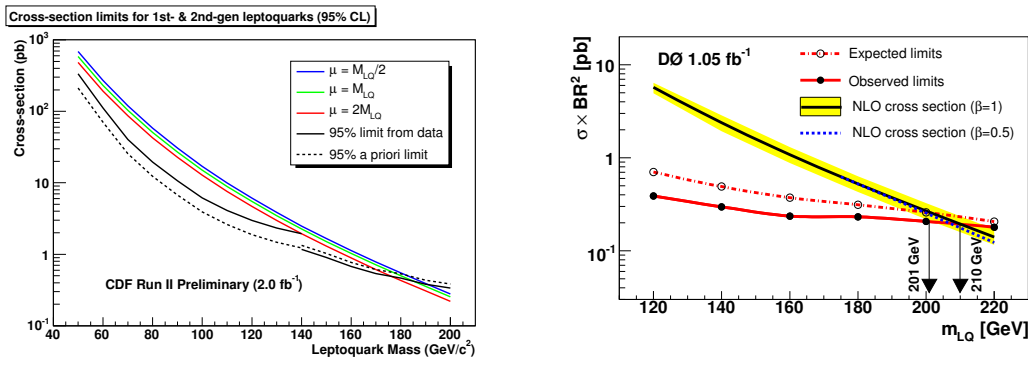


Figure 9: The observed and expected cross-section limits on the pair production of scalar leptoquarks for the first and the second generations from CDF (left), and for the third generation from D0 (right). Theoretical predictions for different renormalization scales are also shown. The discontinuity of CDF limits is due to the use of low/high kinematic regions for mass below/above 140 GeV/ $c^2$  to obtain the best sensitivity.

decay to  $\nu_\ell q$  with a unity coupling. When the renormalization scale  $\mu$  is set to be twice of the leptoquark mass, the lower mass limits on  $LQ_1$  and  $LQ_2$  are 177 GeV/ $c^2$  (see Figure 9). These are currently the world's best limits.

## 2.10. Search for Third Generation Leptoquark in $\tau^+\tau^-b\bar{b}$

Leptoquarks are predicted in many models to explain the observed symmetry between leptons and quarks, such as Technicolor [32], grand unification [33], superstrings [18], and quark-lepton compositeness [34]. The D0 collaboration has looked in 1.1 fb $^{-1}$  of data for pair production of third generation scalar leptoquarks<sup>11</sup> ( $LQ_3$ ) in the  $\tau^+\tau^-b\bar{b}$  final state [35]. Both charge 2/3 and charge 4/3 leptoquarks are included. Events must have a muon with  $p_T > 15$  GeV/ $c$  and  $|\eta_{\text{det}}| < 2.0$ , a hadronic  $\tau$  with visible  $p_T > 15$  GeV/ $c$ , at least two jets with  $E_T > 25, 20$  GeV and  $|\eta_{\text{det}}| < 2.5$  and at least one of the jets must be “ $b$ -tagged” by a neural network algorithm [36]. A maximum requirement on the variable related to the  $W$  boson mass<sup>12</sup>,  $m^* < 60$  GeV/ $c^2$ , is applied to suppress SM background which contains a  $W$  ( $t\bar{t}$  and  $W$  + jets). The dominant backgrounds after all selections are  $Z$  + jets and  $t\bar{t}$  productions. No excess has been observed in either the exactly one  $b$ -tag events (15 observed vs.  $19.6 \pm 2.5$  expected) or the  $\geq 2$   $b$ -tag events (1 observed vs.  $4.8 \pm 1.0$  expected). The variable  $S_T$ , which is the scalar sum  $p_T$  of the muon, hadronic tau, and two highest  $p_T$  jets, is expected to be higher for the  $LQ_3$  signal than for the SM background. The distribution of  $S_T$  is used as a discriminant to set lower mass limits on  $LQ_3$ . The 95% CL lower mass limit on scalar  $LQ_3$  is 210 GeV/ $c^2$  when the coupling constant<sup>13</sup>  $\beta$  is 1 and 207 GeV/ $c^2$  when  $\beta$  is 0.5. Both limits are the world's best limits.

## 2.11. Search for Maximal Flavor Violation in Same-sign Tops

In the model of maximal flavor violation (MxFV) [37], there is at least one new scalar  $\Phi_{FV} \equiv (\eta^+, \eta^0)$  which couples to quarks via  $\Phi_{FV} q_i q_j \propto \xi_{ij}$ , where  $\xi_{i3}, \xi_{3i} \sim V_{tb}$  for  $i = 1, 2$  and  $\xi_{33} \sim V_{td}$  and  $V$  is the CKM matrix [38]. When  $\xi \equiv \xi_{31} = \xi_{13} \sim \mathcal{O}(1) \gg \xi_{23}, \xi_{32} \gg \xi_{33}$ ,  $\eta^0$  decays half of the time to  $t + \bar{u}$  and half the time to  $\bar{t} + u$ . If the charged scalar  $\eta^+$  is too heavy to access at Tevatron or LHC and the neutral scalar  $\eta^0$  is light, a striking signature with same-sign top quark pairs may be produced through  $ug \rightarrow t\eta^0 \rightarrow tt\bar{u} + h.c.$ ,  $u\bar{u} \rightarrow \eta^0\eta^0 \rightarrow tt\bar{u}\bar{u} + h.c.$ ,

<sup>11</sup> Given the null evidence of flavor changing neutral current, leptoquarks of each generation are expected to couple only to fermions of the same generation.

<sup>12</sup> The  $m^*$  is defined as  $\sqrt{2E^\mu E^\nu (1 - \cos\Delta\phi)}$ , where the estimated neutrino energy is  $E^\nu = E_T^\times \left( E^\mu / p_T^\mu \right)$  and  $\Delta\phi$  is the azimuthal angle between the muon and missing energy.

<sup>13</sup> The charge 2/3  $LQ_3$  decays to  $\tau^+b$  with coupling constant  $\beta$  and to  $\bar{\nu}_\tau t$  with coupling  $(1 - \beta)$ .



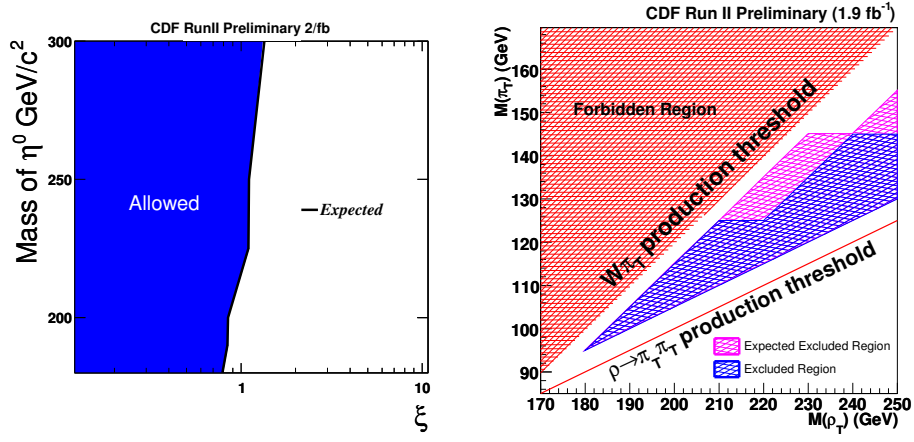


Figure 10: The observed allowed region in the  $m_{\eta^0} - \xi$  plane (left) and the observed and expected excluded regions in the  $M(\pi_T) - M(\rho_T)$  plane. Both analyses are performed by the CDF collaboration.

and  $uu \rightarrow tt + h.c.$ , where the last process comes from  $t$ -channel  $\eta^0$  exchange [39]. The CDF collaboration has searched for same-sign tops predicted by MxFV in  $2.0 \text{ fb}^{-1}$  of data. Events are required to have a pair of same-sign leptons (electron or muon) with  $p_T > 20 \text{ GeV}/c$ ,  $\geq 1$  jet  $b$ -tagged by a jet probability tagging algorithm [40], and  $\cancel{E}_T > 20 \text{ GeV}$ . The dataset has strong sensitivity to this signature: if  $m_{\eta^0} \sim 200 \text{ GeV}/c^2$  and  $\xi \sim 1$ ,  $\sim 11$  MxFV events are expected over a background of  $2.9 \pm 1.8$  events. There are 3 events observed in data, which is consistent with the background prediction, and 95% CL limits are set on  $m_{\eta^0}$  and the coupling  $\xi$ . Figure 10 shows the allowed mass of  $\eta^0$  with respect to  $\xi$ . At  $m_{\eta^0} = 200 \text{ GeV}/c^2$ ,  $\xi < 0.85$ .

## 2.12. Search for Technicolor Particles $\rho_T^0$ and $\rho_T^-$

Technicolor [32] provides an alternative to explain the electroweak symmetry breaking, in addition to the Higgs mechanism. Both mechanisms predict new particles which could be produced in association with a  $W$  boson. Using  $1.9 \text{ fb}^{-1}$  of data, the CDF collaboration has extended its search for SM Higgs,  $p\bar{p} \rightarrow WH_{\text{SM}} \rightarrow Wb\bar{b}$ , to a search for technicolor rhos and pions via the decay chain:  $p\bar{p} \rightarrow \rho_T^- \rightarrow W^- \pi_T^0 \rightarrow \ell \nu_\ell b \bar{b}$  and  $p\bar{p} \rightarrow \rho_T^0 \rightarrow W^- \pi_T^+ \rightarrow \ell \nu_\ell c \bar{b}, \ell \nu_\ell u \bar{b}$ . Events must have a central electron or muon with  $p_T > 20 \text{ GeV}/c$ , exactly two jets with  $E_T > 20 \text{ GeV}$  and  $|\eta_{\text{det}}| < 2.0$ , and  $\cancel{E}_T > 20 \text{ GeV}$ . Three types of  $b$ -tagging requirements are applied: 1. exactly one  $b$ -tagged by the tight SECVTX and a neural network algorithm [4, 41], 2. two  $b$ -tagged, both by the tight SECVTX algorithm, 3. two  $b$ -tagged, one by the tight SECVTX, and one by a jet probability tagging algorithm [40]. These three classes of events have different signal purities and are analyzed separately. Data agree with background prediction in all categories: 805 observed vs.  $810 \pm 159$  expected (class 1), 83 observed vs.  $81 \pm 19$  expected (class 2), and 90 observed vs.  $87 \pm 18$  expected (class 3). The 2-D distribution of dijet mass vs.  $Q \equiv m(\rho_T) - m(\pi_T) - m(W)$  is used as a discriminant to set limits on the masses of techni-pion and techni-rho. Figure 10 shows the excluded region in the  $m(\rho_T) - m(\pi_T)$  plane assuming the Technicolor Strawman model [26]; the results of the three  $b$ -tagging categories are combined.

## 2.13. Search for Long-lived Particles Decaying into $ee$ or $\gamma\gamma$

The D0 collaboration has looked for long-lived particles that decay into final states with two electrons or two photons in  $1.1 \text{ fb}^{-1}$  of data, i.e. a pair of EM showers that originate from the same point in space, away from the  $p\bar{p}$  interaction point [42]. Such long-lived particles arise in fourth generation ( $b'$ ) [43], gauge-mediated SUSY breaking [44], and hidden valleys [45]. Events selected have two central EM clusters with  $E_T > 20 \text{ GeV}$ . This analysis uses the “EM pointing algorithm” as described in Section 2.5 to find the intersection of the trajectories of these two EM objects (secondary vertex). An excess in the positive  $R_{xy}$  compared to the negative  $R_{xy}$  indicates the

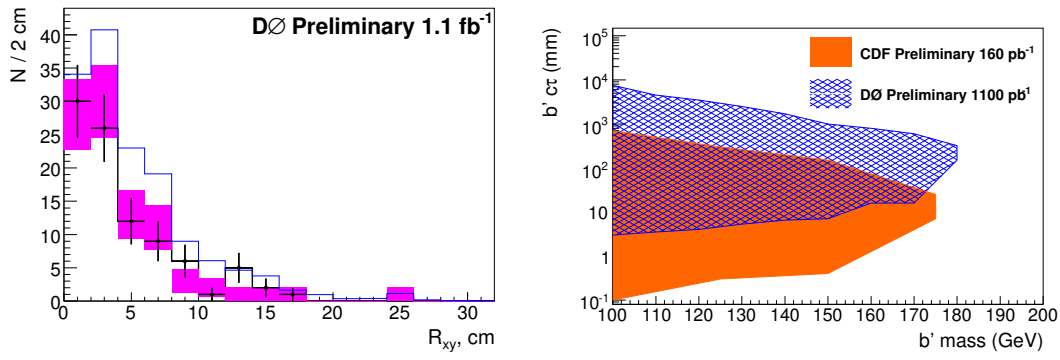


Figure 11: D0 Search for Long-lived Particles Decaying into  $ee$  or  $\gamma\gamma$ . The left figure shows the  $R_{xy}$  distribution observed (markers), and background prediction with error bars (filled histogram). The background prediction is a mirror image of the negative  $R_{xy}$  in data given that SM background is symmetric about  $R_{xy} = 0$ . The expected  $R_{xy}$  for a  $b'$  with mass at 160 GeV/ $c^2$  and  $c\tau$  at 300 mm is also shown. The right figure shows the excluded regions in the  $c\tau(b') - m(b')$  plane by D0 (hatched) and a preliminary CDF search for long-lived particles decaying to  $Z \rightarrow \mu\mu$  (filled).

existence of long-lived exotic particles, where  $R_{xy}$  is the transverse radius from the detector center to the secondary vertex (see Figure 11). No excess is observed and Figure 11 shows the 95% CL limits on the  $c\tau$  and mass of the fourth generation quark  $b'$ . This D0 search is particular sensitive to  $b'$  with large life time ( $c\tau \sim 5 \text{ mm} - 5000 \text{ mm}$ ) while a previous CDF search using  $\mu\mu$  final state [46] is sensitive to  $b'$  with small life time ( $c\tau \sim 0.5 \text{ mm} - 500 \text{ mm}$ ). The two analyses are complementary to each other.

### 3. Conclusion

The CDF and D0 collaborations have performed extensive signature-based searches and searches inspired by non-SUSY models. We have not yet found significant excess in 1.0–2.5 fb $^{-1}$  of data. However, the result of the CDF search for high-mass  $ee$  resonances is exciting: a  $3.8 \sigma$  excess is observed in the region  $228 < M_{ee} < 250 \text{ GeV}/c^2$  with a  $p$ -value of 0.6%. The same analysis will be updated with more data. In addition, similar searches in the  $\mu\mu$  channel by both CDF and D0 are expected in the near future and will help understanding whether the excess is an indication of new physics or a statistical fluctuation. Moreover, several novel detectors and techniques have been developed, such as the CDF EM timing system,  $\cancel{E}_T$  significance model, and the D0 EM pointing algorithm. These allow us to explore signatures which were considered difficult before. As more data are being collected, we expect many new and interesting results from both CDF and D0.

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